THREE SUCCESSFUL TESTS OF COLOR TRANSPARENCY AND NUCLEAR FILTERING*

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Abstract

We review the theoretical formalism for hard exclusive processes in a nuclear medium. Theory suggests that these processes will show the very interesting phenomena of color transparency and nuclear filtering. The survival probability in nuclear media has also been predicted to show a scaling behavior at large momentum and large nuclear number. We show that all of these effects may have already been seen experimentally.

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1. Introduction

Hard QCD processes in a nuclear medium are expected to show the very interesting phenomena of color transparency[1] and nuclear filtering[2,3]. Both of these have been suggested by qualitative theoretical arguements. Partial theoretical proofs based on factorization in the nuclear medium[3] indicate that both phenomena are important for nuclear number $A >> 1$.

Here we report on a systematic study of color transparency and nuclear filtering. We review the theoretical formalism which allows us to separate quasi–exclusive nuclear cross-sections in terms of a perturbative part, non-perturbative wave functions, and their evolution through the nuclear medium. This framework can then be used for phenomenological applications.

An important result is that the usual short distance formalism for exclusive processes may be more applicable to processes in the nuclear medium than to processes in free space. The reason for this is nuclear filtering of soft components of the hadron wave function. Any soft components that may contribute to free space scattering should become depleted in nuclear scattering since the soft components cannot propagate through nuclei. Experimental data available so far seem to support these ideas.

A rather remarkable feature that emerges from our study is the scaling behavior of the nuclear medium effects for large A and Q^2. The nuclear propagation of the hadron is a non-perturbative problem. It is found that one does not need to solve this problem in the large A and large Q^2 limit to check the factorization. Instead, the formalism predicts that survival probabilities should be a function only of the ratio $Q^2/A^{1/3}$ in this limit. This is a test of factorization plus filtering. The functional form of this dependence is theoretically much more model dependent.

2. Theoretical Formalism

By assuming factorization[3] the amplitude M can be written in the light cone gauge as

$$M(Q^2, A) = \left\{ \prod_{i,f} \int [dxd^2k_T] \Big[\psi_A^{(f)*}(x_f, k_{Tf}) H(x_i, x_f, k_{Ti}, k_{Tf}, Q^2) \psi_A^{(i)}(x_i, k_{Ti}) \Big] \right\} \quad (1)$$

where $H(x, k_T, Q^2)$ represents the hard scattering, $\psi_A(x, k_T)$ represents the hadronic wave function inside the nuclear medium and Q^2 is the characteristic momentum scale in the collision. In this equation we are emphasising the internal quark coordinates and suppressing integration over center of mass hadron variables, indicated by curly brackets. The wave function represents the overlap of the short distance hadronic wave function with its propagation through the nuclear medium and can be expressed as

$$\psi_A(x', k'^2_T) = \left\{ \int dx d^2k_T \Big(\delta(x-x')\delta^2(k_T - k'_T) - F_A\Big[s, \Big(\frac{x}{x'}(k_T - k'_T) \Big)^2 \Big] \Big) \psi_0(x, k_T^2) \right\} \tag{2}$$

where $\psi_0(x, k_T^2)$ is the free space hadronic wave function and F_A is the nuclear scattering amplitude. For simplicity here we suppress the i, f indices. The nuclear filtering of soft components of the wave function will require that only the short distance part of the wave function survives. Therefore the function $\psi_{0A}(x, k_T^2)$ may be approximated very well by its short distance form, in contrast to the analogous quantity in free space. Going to the quark transverse separation (b) space we get:

$$\tilde{\psi}_A(x, b) = \tilde{f}_A(s, x, b)\tilde{\psi}_0(x, b), \tag{3}$$

where the tilde's denote the Fourier transforms and $\tilde{f}_A = 1 - \tilde{F}_A$ is the nuclear survival amplitude. The distribution amplitude can then be written as

$$\begin{aligned} \phi_A(x, Q^2) &= \int_0^Q d^2k_T \int d^2b_T e^{i\mathbf{b_T}\cdot\mathbf{k_T}} \tilde{f}_A(s, x, b^2)\tilde{\psi}_0(x, b); \\ &= (2\pi)^2 Q \int_0^\infty db J_1(Qb)\tilde{f}_A(s, x, b^2)\tilde{\psi}_0(x, b). \end{aligned} \tag{4}$$

The above integral will get its dominant contribution from the $b \lesssim 1/Q$ region of the wave function. We assume that the wave function ψ is a slowly varying function of b for small b. This assumption is supported by renormalization group studies. We can then approximate the above integral by replacing the wave function by its value at $b \approx 1/Q$ and cutting off the integral at the same value of b. By substituting this expression into Eq. (1) we see that we have a factorized form for the amplitude M:

$$\begin{aligned} M(Q^2, A) &= \int [dx] \Big\{ \tilde{f}_A(b \approx 1/Q) \Big[\psi_{A0}^{(1)}(x_1, 1/Q) H(x, 0, Q^2) \psi_{A0}^{(2)}(x_2, 1/Q) \Big] \Big\}, \\ &\equiv < \Big\{ \tilde{f}_A(b^i \approx 1/Q) \ldots \tilde{f}_A(b^f \approx 1/Q) \Big\} H(x, 0, Q^2) >, \end{aligned} \tag{5}$$

where the pointed and curly brackets indicate restoration of the integrals over x and hadron center of mass coordinates, respectively, which code information on nuclear size and density. Note that $H(x, 0, Q^2)$ is independent of A and hadron center of mass coordinates for $A >> 1$. The transparency ratio T can then be written as

$$\begin{aligned} T(Q^2, A) &= \frac{d\sigma/dt|_A}{A\ d\sigma/dt|_{free\ space}}; \\ &\cong \frac{| < \{\tilde{f}_A(b^i \approx 1/Q) \ldots \tilde{f}_A(b^f \approx 1/Q)\} H(x, 0, Q^2) > |^2}{A d\sigma/dt_{free\ space}}; \\ &\to P(Q^2, A) R(Q^2), \end{aligned} \tag{6}$$

where N is the number of participating particles that cross the nucleus. The transparency ratio can thus be factorized into two pieces: the survival probability $P(Q^2, A)$ and the ratios of the hard scatterings $R(Q^2)$. The leading Q^2 dependence of the nuclear hard scattering can be obtained by considering the leading order perturbation theory diagrams convoluted with the short distance hadronic wave function.

The above procedure is applicable to all exclusive processes inside nuclei. An interesting prediction of the formalism is that the exclusive processes inside nuclear media will get contribution only from the hard components of the hadronic wave function. Free space exclusive processes show many phenomena, for example oscillations in $pp \to pp$ scattering, helicity violation in elastic hadron-hadron collisions etc., which give indisputable evidence of deviations from the short distance pQCD model. In the nuclear medium, however, we expect that the short distance model will be applicable and should accurately predict the hard cross-sections. Therefore the oscillations in pp elastic scattering should be absent in experiments on large nuclei. Moreover, since only the short distance part of the hadronic wave function is involved inside the nuclear medium, these processes should show color transparency, namely that the effective attenuation cross section goes like $1/Q^2$ for large Q. Finally the survival probability part of the nuclear cross section should depend only on the variable $Q^2/A^{1/3}$ for large Q and large A. As we discuss in the next section all of these predictions are nicely confirmed by the BNL experiment on color transparency.

3. Experimental Confirmation

We next show that the BNL experiment[4] is consistent with all of the tests considered above. The fact that the oscillations are absent in the nuclear cross section was pointed out in Ref. (3) immediately after the data was published. However, since this indicated that the relation of the free space to nuclear hard scattering was more subtle than previously assumed, it was not clear how to separate the survival probability from the (unknown) nuclear hard scattering rate.

The fact that the BNL experiment also shows color transparency was understood only recently[5] with the introduction of a new method to analyze such experiments. The method is based on Eq. (6) and looking at the A dependence of the data at fixed Q^2. If the nucleus is becoming more transparent at larger Q^2 then the *curvature* of the A dependence will become smaller, approaching zero in the limit of perfect transparency. This trick allows an attenuation cross section to be extracted without biasing the analysis with any model for the ratio $R(Q^2)$. As shown in Ref. (5) the curvature with A indeed decreases in going from $Q^2 = 4.8$ GeV^2 to $Q^2 = 8.5$ GeV^2. The effective attenuation cross section σ_{eff} extracted from the data goes roughly like $\sigma_{eff} = 40$ mb 2.2 GeV$^2/Q^2$. The new data analysis procedure also allows independent extraction of the ratio $R(Q^2)$ of the hard scattering cross sections as defined in Eq. (6). The hard scattering cross section in large nuclei was found to follow rather closely the prediction of the short distance model, again confirming the prediction

that the nucleus filters out most of the soft components.

The scaling law for the survival probability was predicted in Ref. (6). However at that time the relation between the survival probability and the transparency ratio was unclear. The theoretical formalism suggests that the transparency ratio is equal to a function of Q^2 times the survival probability. Given enough data this function as well as the survival probability can be extracted from data without any further theoretical input. However at present we have limited data and to check the scaling law we use the short distance model for the nuclear hard scattering: $d\sigma^{hard}/dt \sim \alpha_s(Q^2)^{10}s^{-10}$. This allows us to extract the survival probability. The survival probability extracted in this fashion is found to to be a function of $Q^2/A^{1/3}$, confirming the scaling law.[7] This is an independent successful test: it is shown in Fig. (1).

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Fig. 1. Scaling dependence. The survival probability/constant as a function of the variable Q^2/A^α for the BNL data for three different values of α. One universal curve could fit all the data for $\alpha = 1/3$.